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PHOTONIC BANDGAP EFFECT IN DISORDERED ARRAYS OF SCATTERERS: IMPLICATIONS TO BROADBAND, LOW-LOSS WAVEGUIDING

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Abstract *We demonstrate waveguiding of surface plasmon polaritons along channels through arrays of randomly located surface scatterers, constituting an amorphous (two-dimensional) photonic "crystal" that exhibits a broader stop-band and lower bend loss than conventional periodic configurations.*

Introduction

Photonic crystals (PCs) and the photonic bandgap (PBG) effect have attracted considerable attention in recent years [1]. In particular, the combination of two-dimensional PBG structures and planar waveguide technology holds great promise for future integrated optical circuits [2]. The spectral width of the PBG and its dependence on the propagation direction are important parameters for applications of the PBG structures to optical communications, especially in WDM devices. Conventional PCs have well-defined spatial periods of modulation in refractive index, which depend on the direction of propagation. For a full PBG to be realized, the bandgap for all directions must overlap, typically requiring a high index contrast. Pseudo-periodic configurations with increased rotational symmetry have been suggested as a means of reducing the directional dependence [3]. In the present paper, however, we demonstrate efficient in-plane waveguiding of surface plasmon polaritons (SPPs) through disordered 2D arrays of surface scatterers, having no *a priori* spatial periods or lattice vectors. When the density of scatterers is sufficently high, disordered arrays are found to exhibit a wider omni-directional PBG than periodic PCs fabricated in the same system, and the waveguides have a lower bend loss. We conclude that disordered PBG structures are potentially better suited for realizing integrated optical circuits for optical communication systems than the conventional PCs.

Experiment

As a model system, we investigate the propagation of SPPs along the surface of a gold layer through channels cut in arrays of randomly located gold bumps. We have previously demonstrated waveguiding of SPPs through a corresponding PC structure consisting of regularly spaced bumps [4] and investigated in detail the propagation and bend loss in such waveguides [5,6].

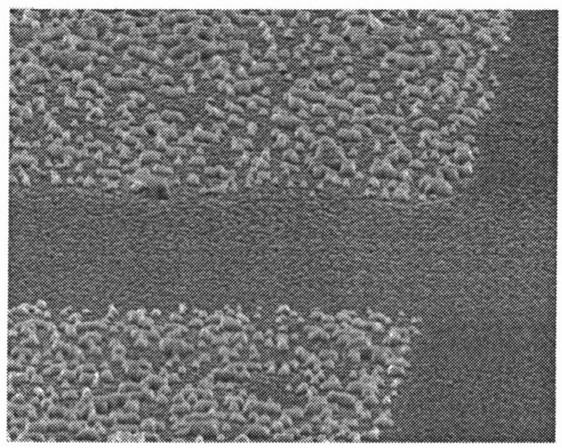

Figure 1: Random array of gold bumps (nominal density: 75 μm^{-2}) on a gold surface, with 2-μm-wide channels, acting as waveguides for surface plasmon polaritons.

The samples used in the present study were fabricated by depositing a ~55-nm-thick layer of gold on a glass substrate. Randomly generated arrays of dots (nominal areal density N=50, 75, and 100 μm^{-2}) were written, using electron-beam lithography, in a resist layer deposited on the gold film. The pattern was transferred to the surface by an additional 70-nm-thick gold film deposition and lift-off. Typical isolated bumps have a diameter of 50 – 100 nm, but closely spaced bumps tend to coalesce and form larger islands due to proximity effects in the exposure. Straight and bent waveguides were written in the structure by removing 2-μm and 3-μm-wide channels of dots in the mask design. Waveguides with 10º and 20º bends were fabricated, having a bend radius of approximately 15 μm. A typical surface structure is shown in Fig. 1.

Excitation of SPPs was done in the Kretchmann configuration [7], using a tunable Ti:sapphire laser. The SPP propagation was imaged with a scanning near-field optical microscope (SNOM) whose images replicate the SPP field intensity distribution along the sample surface. The experimental set-up is described in more detail in Ref. [4].

Results

Experiments were performed using different excitation wavelengths in the range 710 – 860 nm. Optimum conditions for SPP waveguiding were observed in samples with N=75 μm^{-2}. Figure 2 shows SNOM images of three 2-μm-wide waveguides through such a structure, recorded at three different excitation wavelengths. The excited SPP is incident from below and penetrates only a short distance into the array of bumps because of the SPP localization caused by multiple scattering in the plane. The penetration distance increases with wavelength (from ~2 μm at λ = 713 nm to ~6 μm at λ = 795 nm) due to a decrease in the scattering cross section of bumps [7].

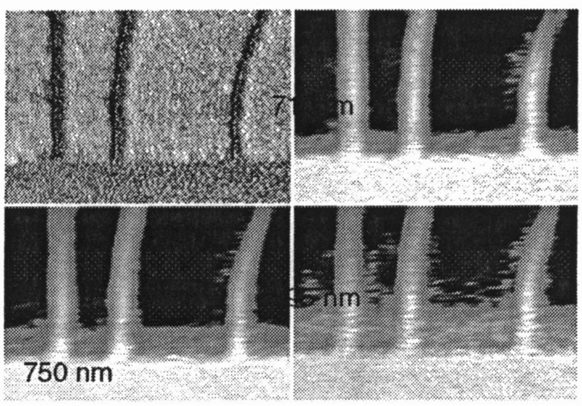

Figure 2: Waveguiding of surface plasmon polaritons at different excitation wavelengths. The top left figure illustrates the topography of the sample surface. Each image represents the same 32 μm × 22 μm area. The plasmon polaritons propagate from bottom to top in the figures.

The excitation wavelength dependence reveals a significant increase in the spectral width of the PBG ($\Delta\lambda$), as compared to periodic structures. Confined waveguide modes and complete extinction of the SPP intensity inside the structure is observed in the wavelength range 725 – 785 nm in the disordered structure ($\Delta\lambda \sim 0.08\,\lambda$). This range is several times larger than that observed for a triangular lattice structure with the lattice constant of 440 nm [5].

By making cross-sectional cuts through the SNOM image, the total intensity and FWHM of the waveguide modes can be directly measured. We find a FWHM of ~1.5 μm, which is identical to what was observed for the SPP waveguides of similar width in a periodic PBG structure [5]. The SPP propagation length in straight channels is similar to the theoretical value for the SPP propagation along a flat film surface (~16 μm), meaning that no additional waveguide loss was observed. Furthermore, comparing straight waveguides with those having 10º and 20º bends, we detect no additional bend loss within our experimental uncertainty (< 0.4 dB). This is a significant improvement over the ~2 dB loss reported for 20º bends in a conventional SPP-PBG waveguide [6]. Evidence of strong SPP localization in the random PBG structure is observed in the form of bright spots located near the channel bends. Finally, the SPP scattering out of the plane was found to be minimal, as evidenced by a complete extinction of the optical signal when the probe tip of the SNOM is retracted away from the surface.

Conclusions

Using SPPs propagating on a metal surface, we have demonstrated that random arrays of scatterers can lead to strong inhibition of light propagation over a wider wavelength range than observed in conventional (periodic) PBG structures. Curved waveguides through a random PBG structure were also found to exhibit noticeably lower bend loss than through a periodic PBG structure, presumably due to the inherent lack of directional dependence of the PBG in a disordered structure.

The structures investigated here are not directly suited for applications in integrated optics, due to the short propagation SPP length. However, similar structures can be designed for the wavelength range around 1.55 μm, where the SPP propagation length extends over hundreds of micrometers. Furthermore, the principle of waveguiding along channels through a random array of scatterers is applicable to other systems where multiple scattering of light is utilized to control light propagation on a wavelength scale. The resulting improvements in performance can be exploited in designing low-loss photonic circuits for WDM applications.

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